New measurement of the B^0_s mixing phase and observation of suppressed B^0_s decays at CDF

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DISCRETE2010

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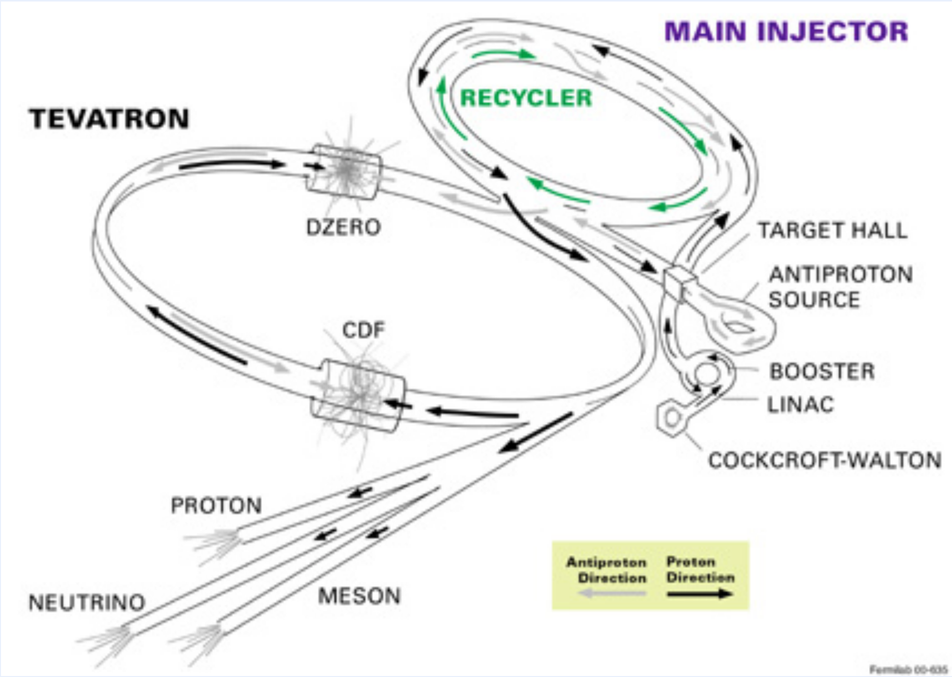
Overview

Recent CDF B_s^0 analyses:

- Updated measurement of $\sin(2\beta_s)$
  - Using 5.2 fb^{-1} integrated luminosity
  - Improved Particle ID and flavour tagging
- Calibration of Same Side Kaon Tagger through B_s^0 mixing measurement
  - Important flavour tagger for β_s analysis
- Observation of 2 suppressed B_s^0 decay channels
  - B_s->$J/\psi K^*$
  - B_s->$J/\psi K_s$

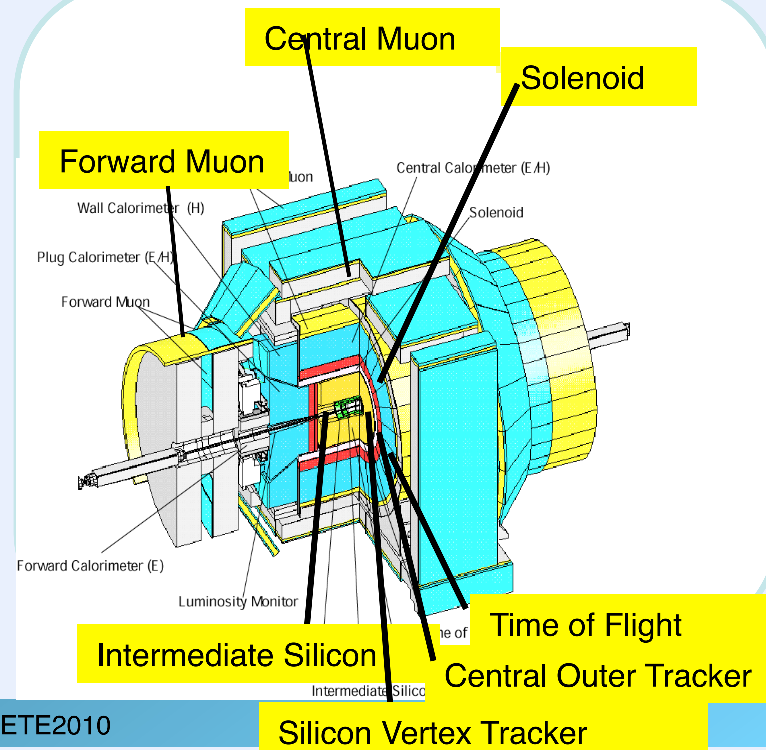
CDF at the Tevatron



- p-pbar collisions at 1.96TeV
- Constantly improving luminosity performance
  - peak instantaneous luminosity >3x10^{32} cm^{-2}s^{-1}
  - ~8fb^{-1} delivered to the experiments

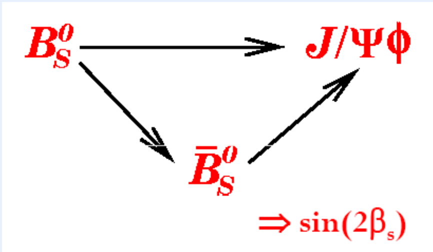
B physics at CDF:

- Particle ID: dE/dx and TOF
- Excellent vertex resolution ~23μm and p_T resolution: $\sigma(p_T)/p_T^2 \sim 0.1\%$
- Di-muon trigger important for B->J/ψX analyses



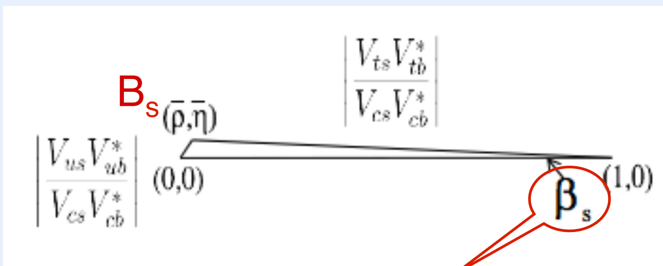
Latest CDF $\sin(2\beta_s)$ results with 5.2 fb^{-1}

Search for New Physics in B_s mixing

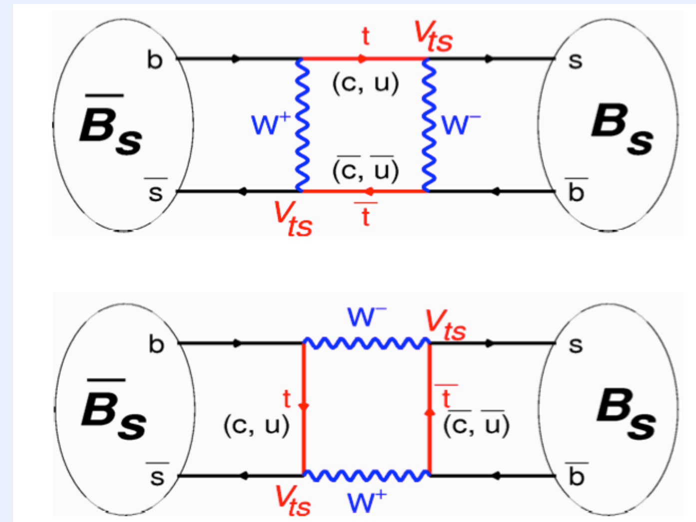


CP violation in $B_s \rightarrow J/\psi\varphi$ occurs through interference of decays with and without mixing.

$$B_s^L = |B^0\rangle + |\bar{B}^0\rangle$$
$$B_s^H = |B^0\rangle - |\bar{B}^0\rangle$$

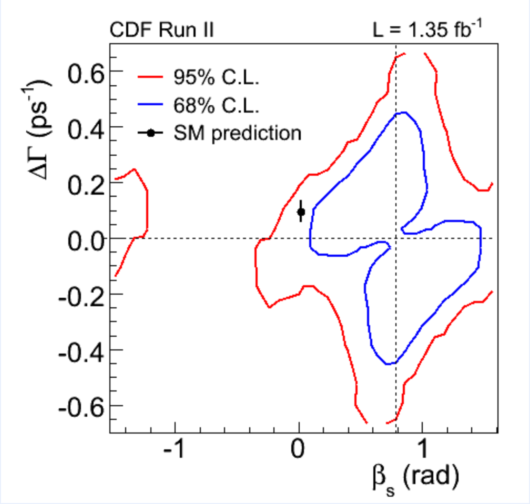


Small SM prediction: clear to see potential excess from NP



- New particles could enter weak mixing box diagrams and enhance CP violation
- Time evolution of flavour tagged $B_s \rightarrow J/\psi\varphi$ decays is very sensitive to New Physics
  - Decay width difference, $\Delta\Gamma$ and mixing phase would be effected by additional NP phase

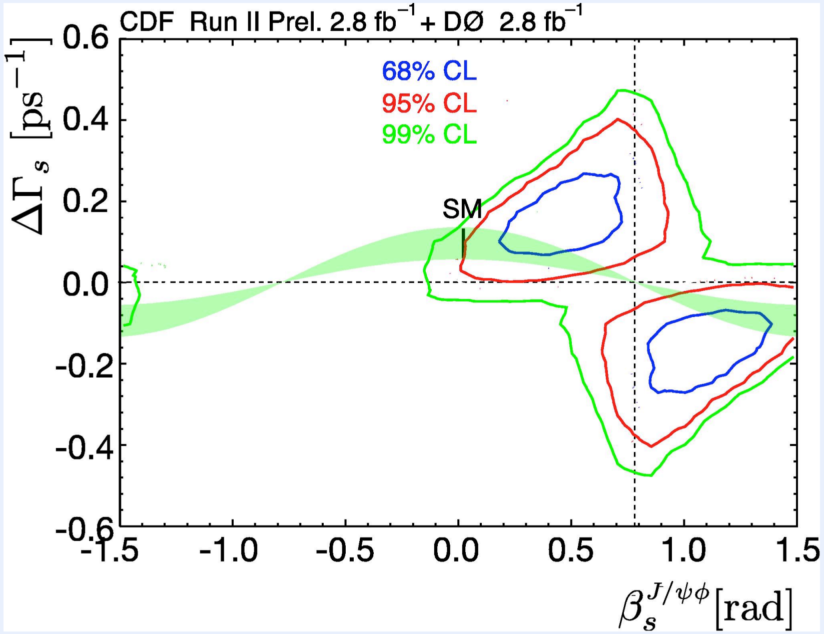
Previous measurements



PRL 100, 161802 (2008)

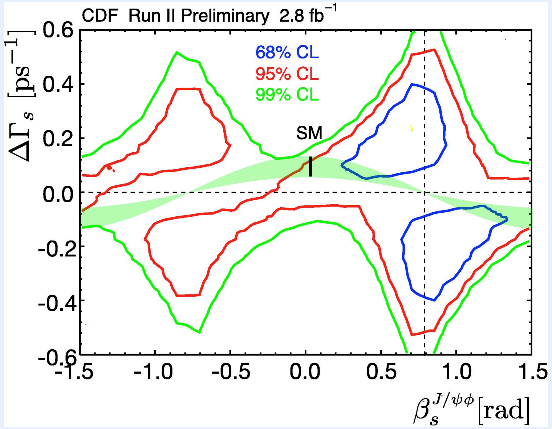
CDF: 1.3fb^{-1} result

P-value for SM point =15% -> significance 1.5σ



CDF: 2.8fb^{-1} result

P-value for SM point =7% -> significance 1.8σ



CDF Public Note 9458

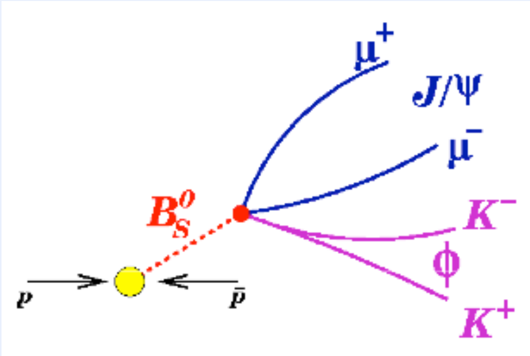
Tevatron combination: probability of observed deviation from SM = 3.4% (2.12 σ)

CDF Public Note 9787

Behaviour of likelihood fit prevents giving β_s measurement as a point value - instead produce likelihood contours

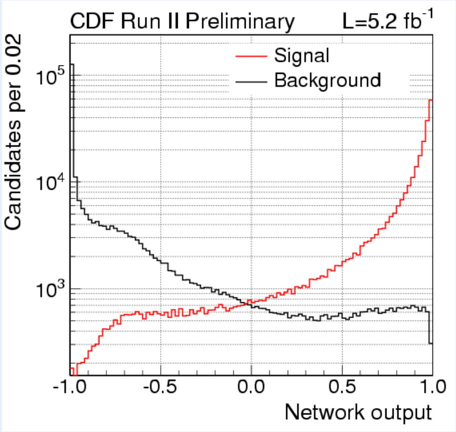
Analysis overview

Reconstruct $B_s \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\ \phi(\rightarrow K^+K^-)$



Di-muon trigger

NN selection



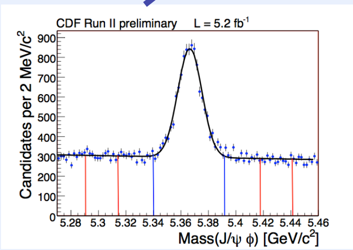
Simultaneous mass, angular, time dependent, flavour tagged fit

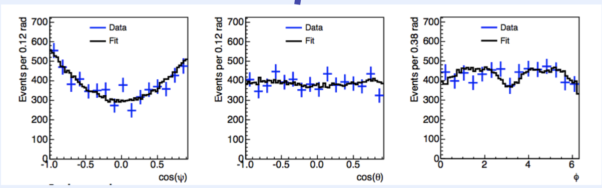
B_s mass fit to separate signal from bkg

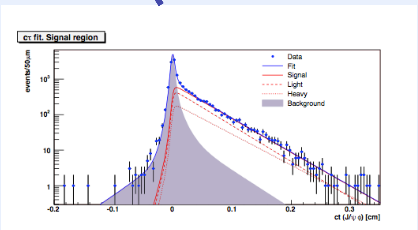
Angular separation of CP eigenstates

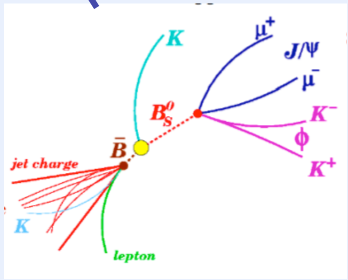
Time dependence of decay

Flavour tagging to separate B_s and $\overline{B}_s$ decays





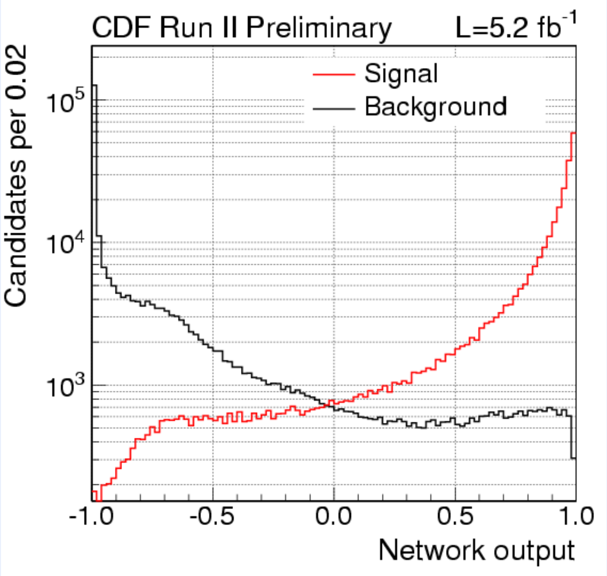




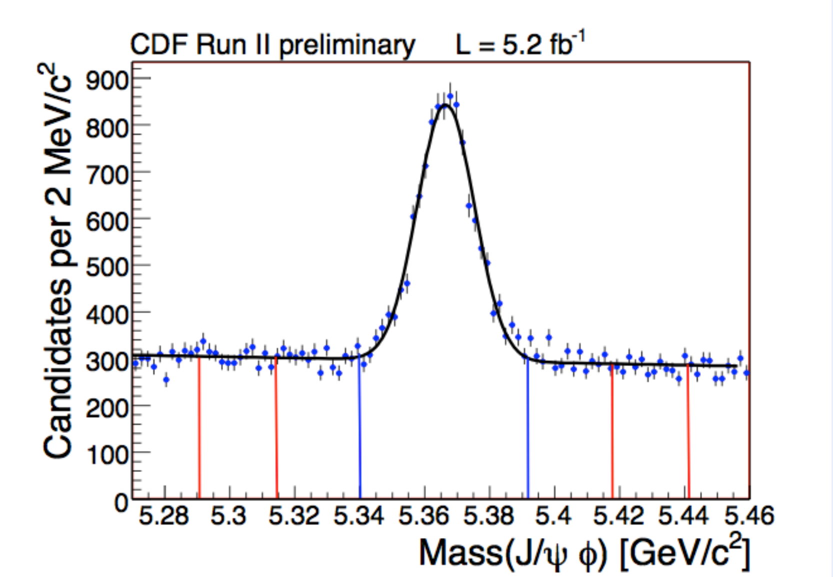
Data sample and selection for update

Statistically limited analysis - high quality selection is essential:

- Key role of particle ID
  - recalibrated for this result
- Neural network selection
  - optimised on pseudo experiments to minimise statistical errors on β_s



- Integrated luminosity: 5.2fb^{-1}
- Signal events: ~6500 (c.f. 2.8fb^{-1} with ~3150 signal events)



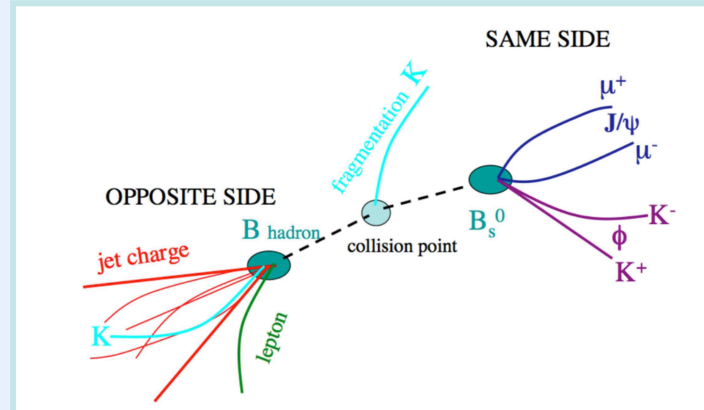
B flavour tagging and the likelihood fit

Opposite side tag (OST):

- Jet charge and lepton charge taggers
- Tag flavour of opposite side *b* quark
- $\varepsilon D^2 \approx 1.2\%$

Same side tag (SST):

- Kaon tags flavour of *s* quark in B_s
- $\varepsilon D^2 \approx 3.2\%$



Fit without flavour tagging, has four fold ambiguity:

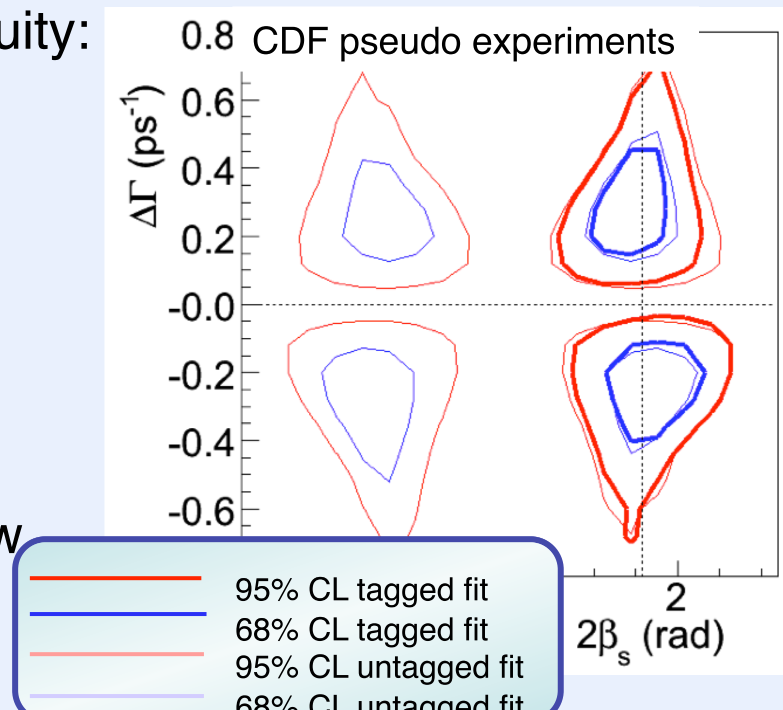
- β_s and $\Delta\Gamma$ symmetric
- strong phases symmetric about pi

$$\begin{aligned} \beta_s &\rightarrow \frac{\pi}{2} - \beta_s \\ \Delta\Gamma &\rightarrow -\Delta\Gamma \\ \phi_{\parallel} &\rightarrow 2\pi - \phi_{\parallel} \\ \phi_{\perp} &\rightarrow \pi - \phi_{\perp} \end{aligned}$$

and

$$\begin{aligned} \beta_s &\rightarrow -\beta_s \\ \Delta\Gamma &\rightarrow -\Delta\Gamma \end{aligned}$$

- Addition of flavour tagging allows us to follow time dependence of B_s and $\overline{B_s}$ separately
  -> Removes half of the ambiguity

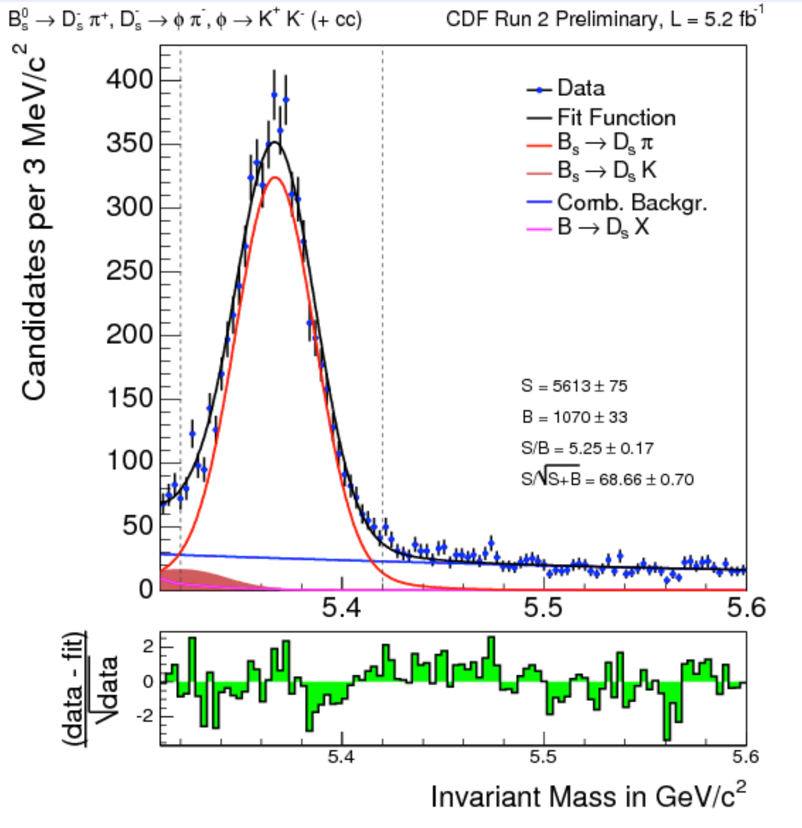


B flavour tagging: SSKT calibration

- SSKT updated for this analysis
- calibrated on B_s mixing measurement
- B_s mixing measured with 5.2fb[-1]
- First CDF calibration of a SSKT on data
- Uses several decay modes:

$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to \phi^0 \pi^-,\ \phi^0 \to K^+ K^-$$
$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to K^* K^-,\ K^* \to K^+ \pi^-$$
$$B_s^0 \to D_s^- \pi^+,\ D_s^- \to (3\pi)^-$$
$$B_s^0 \to D_s^- (3\pi)^+,\ D_s^- \to \phi^0 \pi^-,\ \phi^0 \to K^+ K^-$$

12877±113 combined signal events

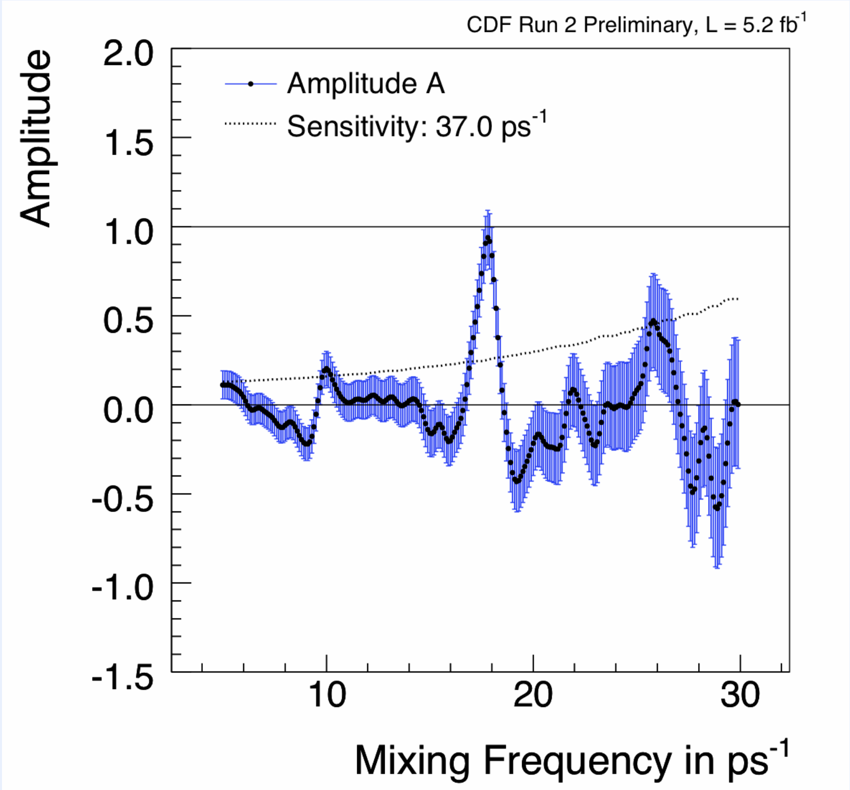


golden mode

http://www-cdf.fnal.gov/physics/new/bottom/100204.blessed-sskt-calibration/index.html

B flavour tagging: SSKT calibration

- Mixing amplitude ≈1 :
  - tagger assesses its performance accurately
- Amplitude > 1
  - tagger underestimates its power
- Amplitude < 1
  - tagger overestimates performance
- Measured amplitude used to scale event by event tagging dilution



$$\boxed{\mathcal{A} = 0.94 \pm 0.15\ (\text{stat.}) \pm 0.13\ (\text{syst.})}$$

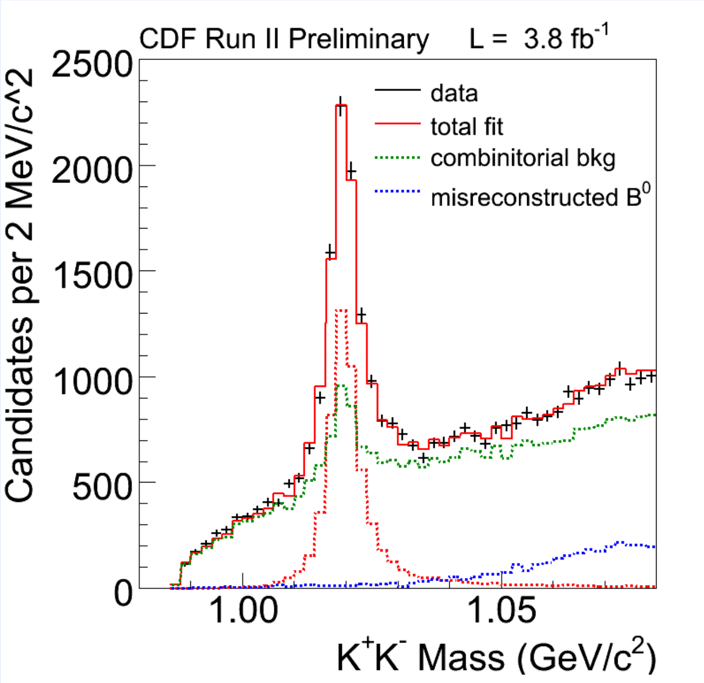
$$\Delta m_s = 17.79 \pm 0.07\ ps^{-1} \quad (\text{stat. only})$$

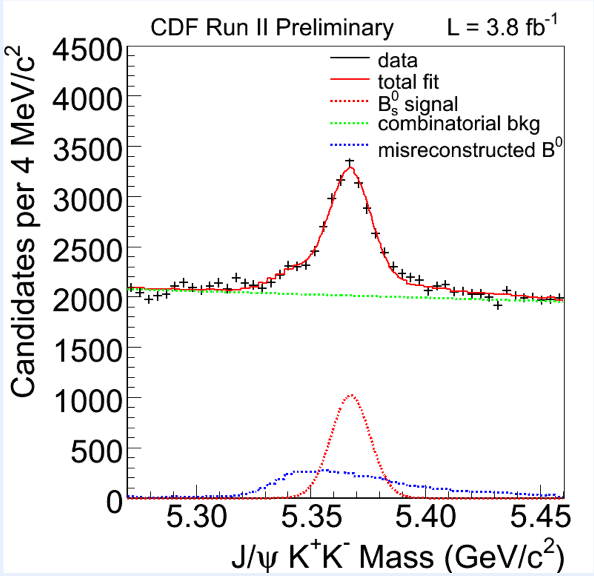
$$\epsilon \mathcal{A}^2 D^2 \approx 3.2 \pm\ 1.4\ \%$$

Agreement between this and the published CDF measurement is very good

S-wave contamination

- Potential contamination of $B_s \to J/\psi\varphi$ signal by: $B_s \to J/\psi$ KK (KK non-resonant) and $B_s \to J/\psi\ f^0$ where KK and f^0 are S-wave states
- Contamination could bias towards SM value of β_s
- S-wave KK component has been added to full angular, time-dependent likelihood fit.



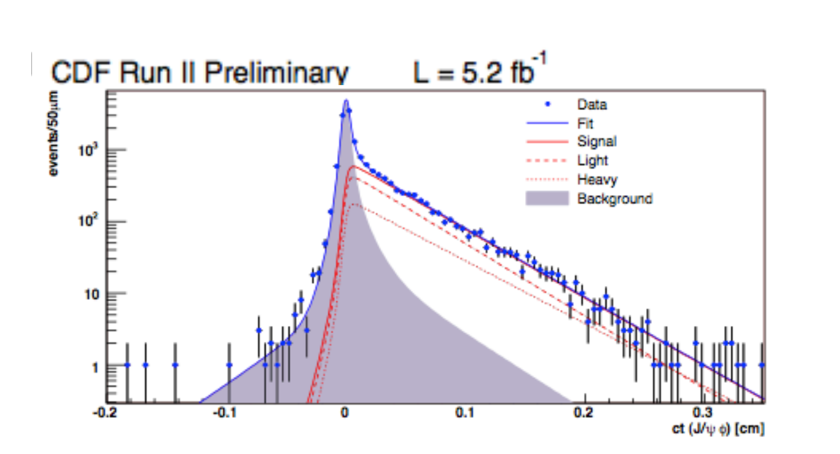


The fitted fraction of KK S-wave contamination in the signal is

< 6.7% at the 95% CL

Checking the fitter: projections

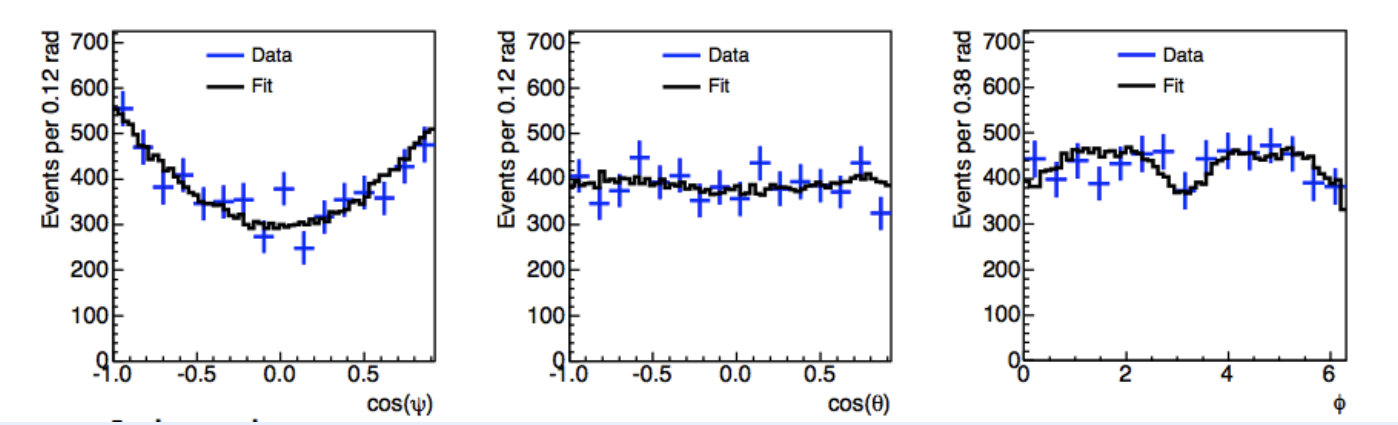
Fit projections on physical parameters such as B_s lifetime used to check performance of the likelihood fit



B_s lifetime distribution consisting of:

- B_s^H (short lived)
- B_s^L (long lived)

- Angular distributions are used to separate CP odd and even final states
- Angular projections used to check our parameterisation of the angular distributions



Flavour tagged fit with β_s =0.0

- Tagged $B_s \to J/\psi\varphi$ likelihood fit
- CP violating phase, β_s = 0 , set to SM prediction

PDG value:

$$\tau_s = 1.47^{+0.026}_{-0.027}\ \mathrm{ps}$$

CDF II Preliminary 5.2fb $^{-1}$

$$\tau_s = 1.53 \pm 0.025\ (\mathrm{stat.})\ \pm 0.012\ (\mathrm{syst.})\ \mathrm{ps}$$

$$\Delta\Gamma = 0.075 \pm 0.035\ (\mathrm{stat.}) \pm 0.01\ (\mathrm{syst.})\ ps^{-1}$$

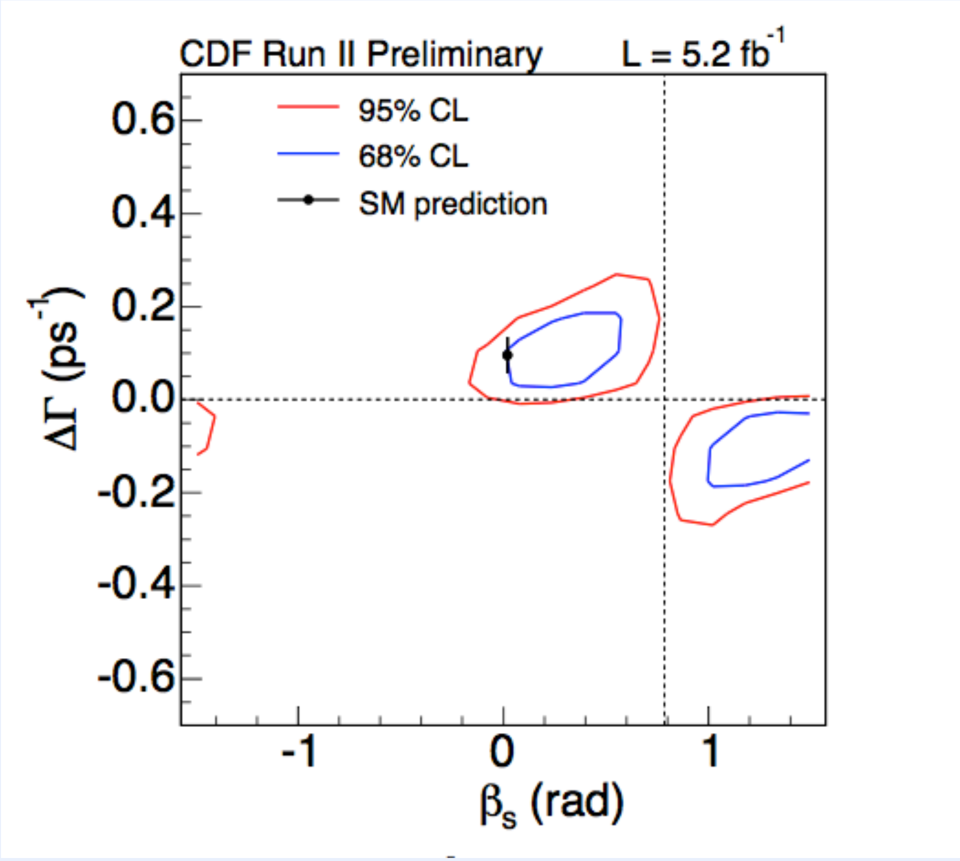
$$|A_{\parallel}(0)|^2 = 0.231 \pm 0.014\ (\mathrm{stat}) \pm 0.015\ (\mathrm{syst.})$$

$$|A_0(0)|^2 = 0.524 \pm 0.013\ (\mathrm{stat}) \pm 0.015\ (\mathrm{syst.})$$

$$\phi_{\perp} = 2.95 \pm 0.64\ (\mathrm{stat}) \pm 0.07\ (\mathrm{syst.})$$

World's most precise single measurement of B_s lifetime and decay width difference

New CDF measurement of β_s



Coverage adjusted 2D likelihood contours for β_s and $\Delta\Gamma$

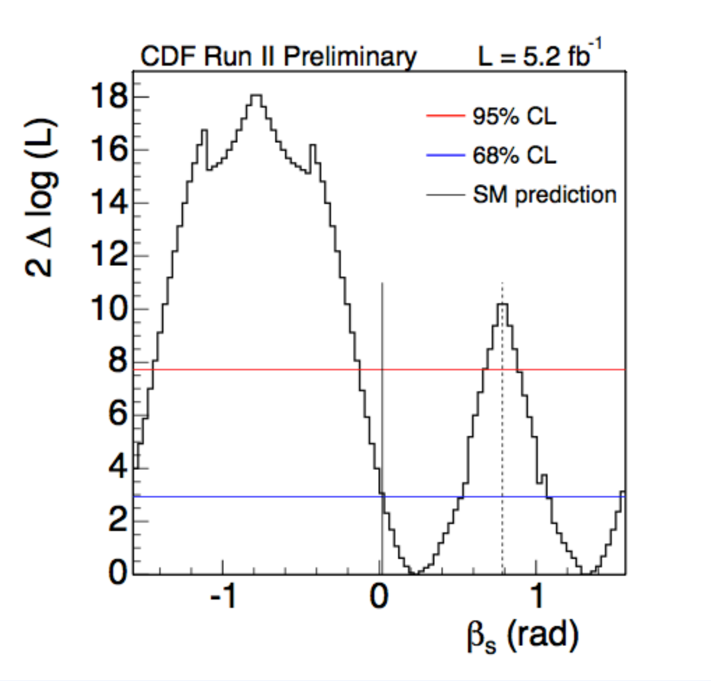
P-value for SM point: 44% (0.8σ deviation)

(68% CL):

$$[0.02, 0.52] \cup [1.08, 1.55]$$

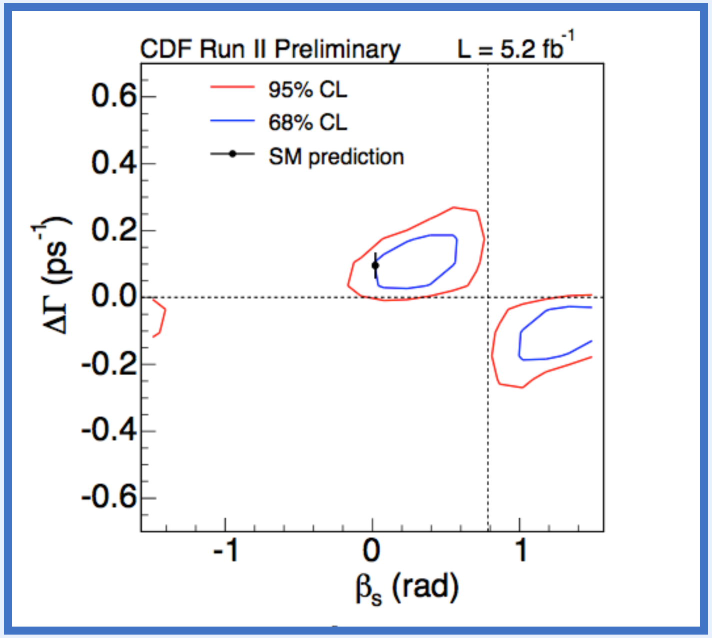
(95% CL):

$$[-0.13, 0.68] \cup [0.89, \pi/2]$$
$$\cup[-\pi/2, -1.44]$$

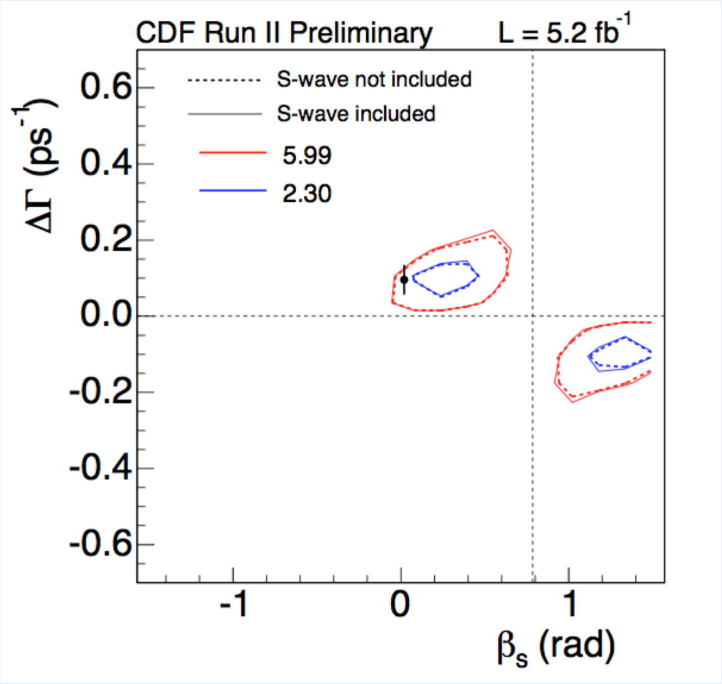


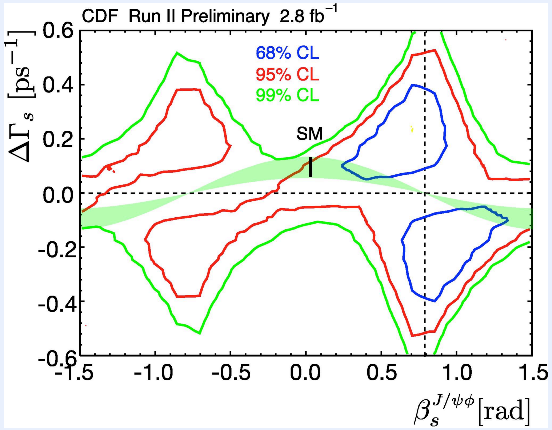
Comparisons

new CDF result



2D likelihood contours for β_s and $\Delta\Gamma$ without coverage adjustment





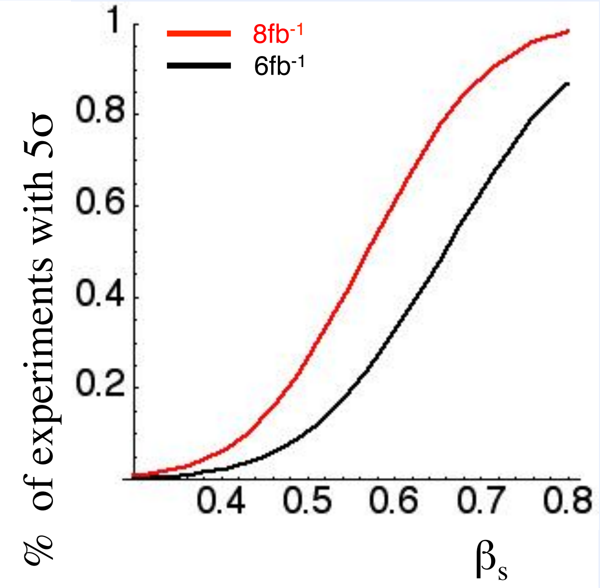
CDF ICHEP 2008 result

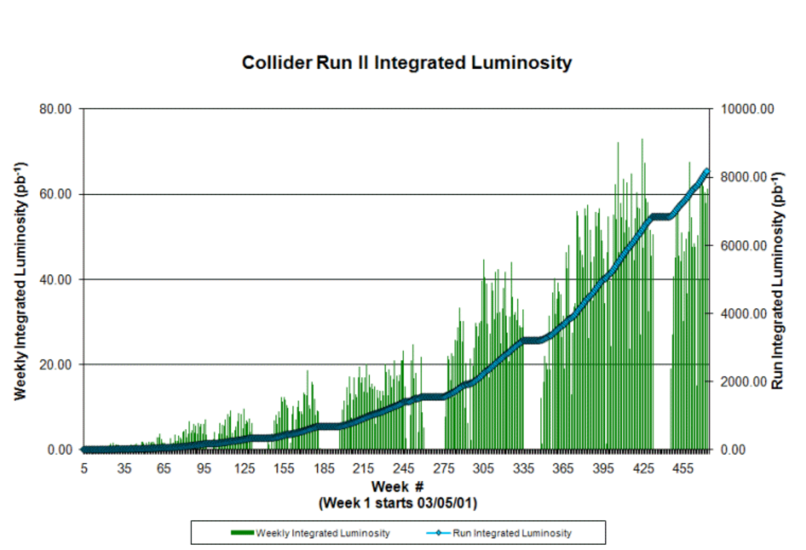
Inclusion in the fit of S-wave KK (f^0) contamination to phi meson signal has small effect on likelihood contours

Future prospects

- Tevatron delivering record luminosity, CDF records ~60pb^{-1} per week
- End of 2011: double again the dataset, further improvements to analysis
- Search for NP in B_s^0 mixing at CDF has potential to observe/ exclude wide range of non-SM mixing phase values
- Investigating other channels related to this physics – such as recently observed

$B_s \rightarrow J/\Psi\ K_s$ and $B_s \rightarrow J/\Psi\ K^*$





Observation of new suppressed B_s^0 decays and measurement of their branching ratios

Suppressed B_s decays

Observation of previously unseen B_s decays:

$B^0_s \rightarrow J/\Psi K_s$

$B^0_s \rightarrow J/\Psi K^*$

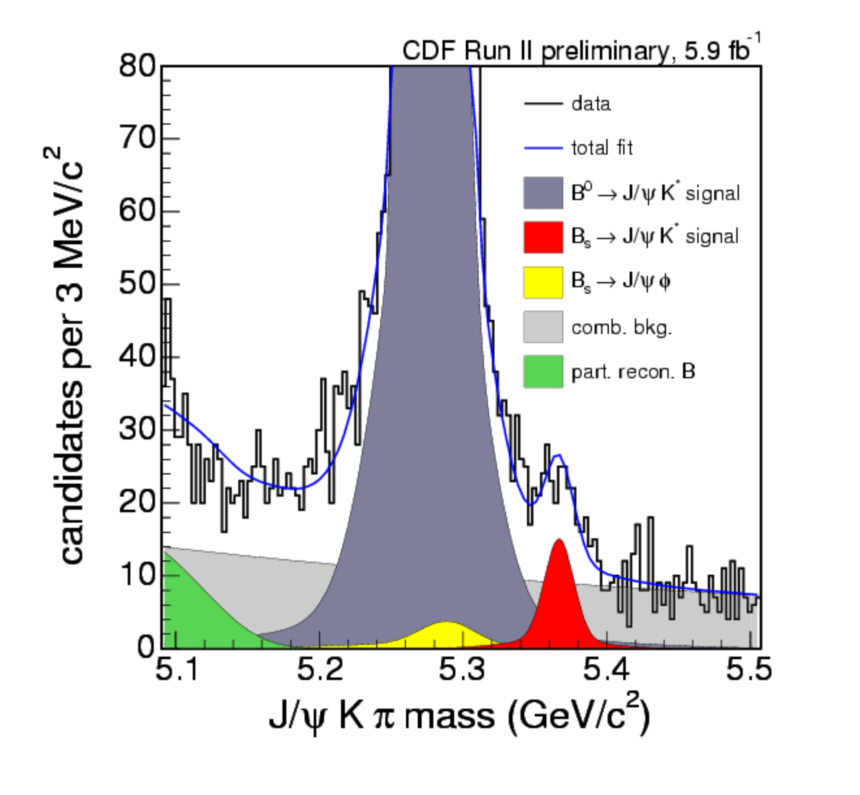
- Binned maximum likelihood fit to find ratios of B^0 and B_s^0 to each final state
- Exploit strong mass and lifetime resolution
- 3 Gaussian templates used to model both B^0 and B_s^0
- Exponential models combinatorial background
- Relative acceptance factor calculated from MC

http://www-cdf.fnal.gov/physics/new/bottom/100708.blessed-BsJpsiK/cdf10240_SuppresBsPublicNote.pdf

Suppressed B_s decays

$B_s \rightarrow J/\Psi\ K^*$

- Admixture of *CP* states
- Possible extraction of $\sin(2\beta_s)$
- 8 σ significance
- Yield: 151 ± 25
- B^0->$J/\psi\ K^*$ yield: 9530±110

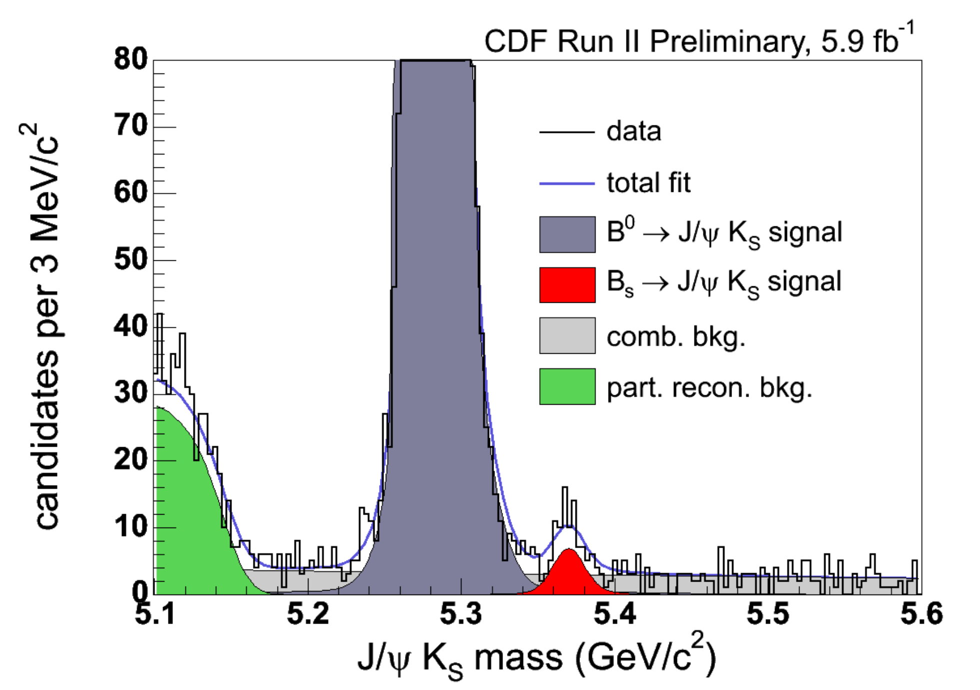


$$\frac{BR(B_s^0 \rightarrow J/\psi K^*)}{BR(B^0 \rightarrow J/\psi K^*)} = (0.041 \pm 0.007\ (\mathrm{stat.})\ \pm 0.004\ (\mathrm{syst.})\ \pm 0.005\ (\mathrm{frag.}))$$

Suppressed B_s decays

$B_s \rightarrow J/\Psi K_s$

- pure *CP* odd state
- access to B_s^H lifetime
- access to unitarity triangle angle γ
- 7.2 σ significance
- Yield: 64 ± 14
  - $B^0 \rightarrow J/\psi K_s$ yield: 5954±79



$$\frac{BR(B_s^0 \rightarrow J/\psi K^0)}{BR(B^0 \rightarrow J/\psi K^0)} = (0.062 \pm 0.009\ (\text{stat.})\ \pm 0.025\ (\text{syst.})\ \pm 0.008\ (\text{frag.}))$$

Summary

Updated CDF search for NP in $B_s^0 \rightarrow J/\psi\varphi$

- Tightened constraints on CP violating phase β_s

$$[0.02, 0.52] \cup [1.08, 1.55] \quad \textbf{(68\% CL)}$$
$$[-0.13, 0.68] \cup [0.89, \pi/2] \cup [-\pi/2, -1.44] \quad \textbf{(95\% CL)}$$

- P-value for SM point: 44% (0.8σ)
- World's best measurement of B_s lifetime and decay width difference in hypothesis of no CP violation
- SSKT calibrated on updated B_s mixing measurement

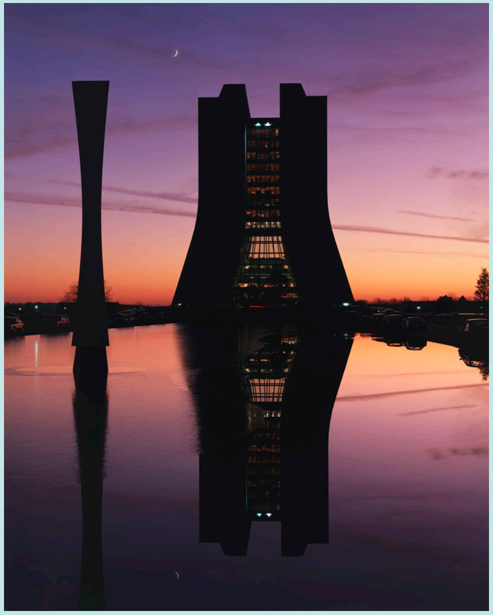
First observation of 2 suppressed B_s decays, with high significance

- Measurement of Branching Ratios

$$BR(B_s^0 \rightarrow J/\psi K^*) = (8.3 \pm 1.2\ (\mathrm{stat.})\ \pm 3.3\ (\mathrm{syst.})\ \pm 1.0\ (\mathrm{frag.})\ \pm 0.4\ (\mathrm{PDG})) \times 10^{-5}$$
$$BR(B_s^0 \rightarrow J/\psi K^0) = (3.53 \pm 0.61\ (\mathrm{stat.})\ \pm 0.35\ (\mathrm{syst.})\ \pm 0.43\ (\mathrm{frag.})\ \pm 0.13\ (\mathrm{PDG})) \times 10^{-5}$$

- With sufficient statistics, both could be used to extract parameters of interest for CP violation measurements

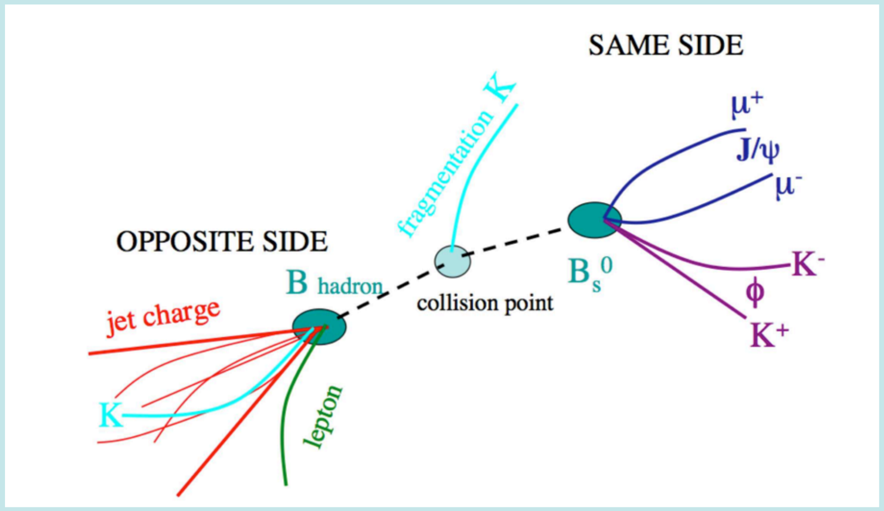
Back up



B flavour tagging at CDF

Opposite side tag (OST):

- b quarks are pair produced (strong interaction -> flavour conservation)
- Can deduce properties of the candidate *B* meson from decay of the *B* hadron formed by the pair produced partner of its *b* quark
- *b* or $\bar{b}$ content of charged opposite side *B* can be identified by
  - Jet charge
  - Lepton charge (e, μ)
- $\varepsilon D^2 \approx 1.2\%$



Same side kaon tag (SSKT):

- Sign of kaon from primary vertex of candidate *B* can tag B_s or $\bar{B}_s$ flavour
- Kaon contains the pair produced *s* ($\bar{s}$) quark of the B_s
- $\varepsilon D^2 \approx 3.2\%$

Important tagging parameters:
tag decision, tagging dilution (weight) and tagging efficiency

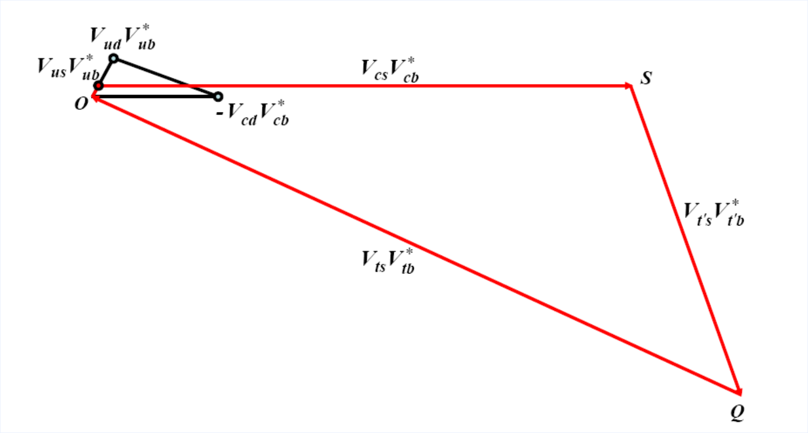
Inclusion of S-wave KK component

- S-wave KK component has been added to full angular, time-dependent likelihood fit.
- Both f_0 and non-resonant KK are considered flat in mass within the small selection window,
- φ meson mass is modelled by asymmetric, relativistic Breit Wigner
- J/ψ KK (f_0) is pure CP odd state -> follows time dependence of CP odd component of $B_s \rightarrow \Psi\phi$
- KK mass is NOT a fit parameter

The fitted fraction of KK S-wave contamination in the signal is
< 6.7% at the 95% CL

Potential NP contributions

- 4th generation could enhance the weak mixing diagram in the neutral B_s system
- George W.S. Hou suggests the *t'* as a possible contribution to the mixing box diagrams
- SM contains the ingredients to generate the 100% Baryon Asymmetry of the Universe (BAU)
- Predicted CP violation from 3 generations is negligible compared to what is observed in BAU
- 4th generation of quarks would lead to "unitarity quadrangle"
  -> enhances SM CP violation by 10 orders of magnitude!



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* + V_{t's}V_{t'b}^* = 0$$

arXiv:0803.1234v3 George W.S. Hou

Systematic errors

- Systematic study for point estimates uses pseudo experiments to estimate potential effects of any mis-parameterisations in the fitter.
- 2 techniques used:
  - Generating pseudo experiments using an altered parameterisation, fitting with default model
  - Generating pseudo experiments according to histograms of real data distribution

Systematic	$\Delta\Gamma$	$c\tau_s$	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\phi_\perp$
Signal efficiency:					
Parameterisation	0.0024	0.96	0.0076	0.008	0.016
MC reweighting	0.0008	0.94	0.0129	0.0129	0.022
Signal mass model	0.0013	0.26	0.0009	0.0011	0.009
Background mass model	0.0009	1.4	0.0004	0.0005	0.004
Resolution model	0.0004	0.69	0.0002	0.0003	0.022
Background lifetime model	0.0036	2.0	0.0007	0.0011	0.058
Background angular distribution:					
Parameterisation	0.0002	0.02	0.0001	0.0001	0.001
$\sigma(c\tau)$ correlation	0.0002	0.14	0.0007	0.0007	0.006
Non-factorisation	0.0001	0.06	0.0004	0.0004	0.003
$B^0 \to J\psi K^*$ crossfeed	0.0014	0.24	0.0007	0.0010	0.006
SVX alignment	0.0006	2.0	0.0001	0.0002	0.002
Mass error	0.0001	0.58	0.0004	0.0004	0.002
$c\tau$ error	0.0012	0.17	0.0005	0.0007	0.013
Pull bias	0.0028		0.0013	0.0021	
Totals	0.01	3.6	0.015	0.015	0.07

Point estimates: results comparison

$$\begin{aligned} c\tau &= 458.64 \pm 7.54 \text{ (stat.) } \mu m \\ \Delta\Gamma &= 0.075 \pm 0.035 \text{ (stat.) } ps^{-1} \\ |A_{\|}|^2 &= 0.231 \pm 0.014 \text{ (stat.)} \\ |A_0|^2 &= 0.524 \pm 0.013 \text{ (stat.)} \\ \phi_{\perp} &= 2.95 \pm 0.64 \text{ (stat.)} \end{aligned}$$

Tagged, with S-wave

$$\begin{aligned} c\tau &= 459.1 \pm 7.7 \text{ (stat.) } \mu m \\ \Delta\Gamma &= 0.073 \pm 0.03 \text{ (stat.) } ps^{-1} \\ |A_{\|}|^2 &= 0.232 \pm 0.014 \text{ (stat.)} \\ |A_0|^2 &= 0.523 \pm 0.012 \text{ (stat.)} \\ \phi_{\perp} &= 2.80 \pm 0.56 \end{aligned}$$

Tagged, no S-wave

Untagged, with S-wave

$$\begin{aligned} c\tau &= 456.93 \pm 7.69 \text{ (stat.) } \mu m \\ \Delta\Gamma &= 0.071 \pm 0.036 \text{ (stat.) } ps^{-1} \\ |A_{\|}|^2 &= 0.233 \pm 0.015 \text{ (stat.)} \\ |A_0|^2 &= 0.521 \pm 0.013 \text{ (stat.)} \end{aligned}$$

Untagged, no S-wave

$$\begin{aligned} c\tau &= 457.2 \pm 7.9 \text{ (stat.) } \mu m \\ \Delta\Gamma &= 0.070 \pm 0.04 \text{ (stat.) } ps^{-1} \\ |A_{\|}|^2 &= 0.233 \pm 0.016 \text{ (stat.)} \\ |A_0|^2 &= 0.520 \pm 0.013 \text{ (stat.)} \end{aligned}$$

Measurement of β_s: coverage adjustment

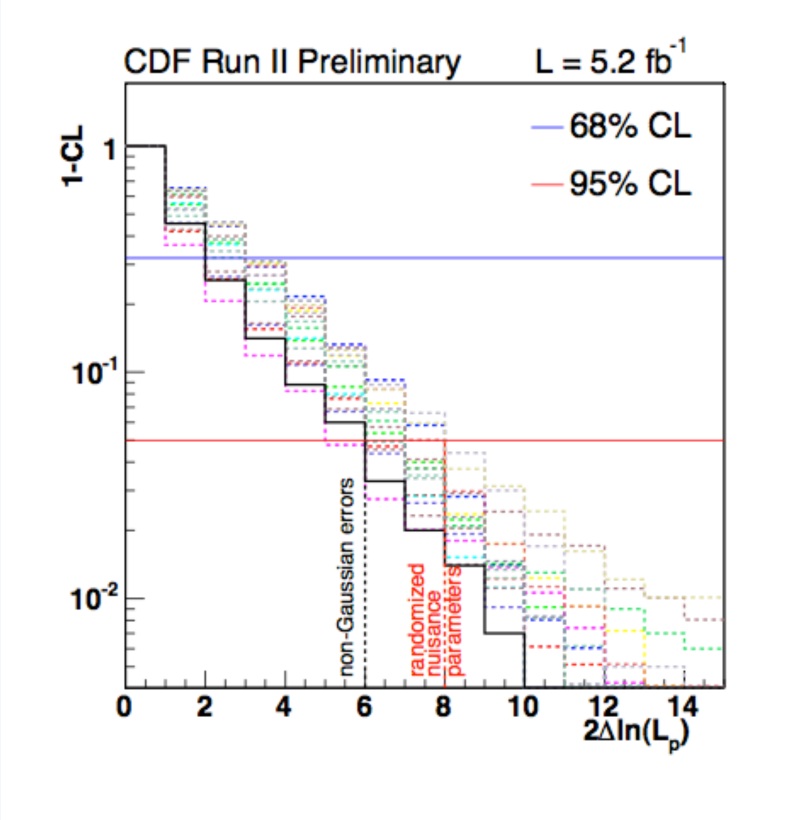
Use likelihood ratio ordering technique to account for non-Gaussian behaviour (ensure confidence regions not under-covered) and to include effect of systematics on the errors:

- Generate pseudo experiments at the SM point in the $\Delta\Gamma$-β_s plane.
- Fit with all parameters floating
- Fit again with $\Delta\Gamma$ and β_s fixed to the SM point
- Form a likelihood ratio:

$$\mathcal{LR} = 2\log\frac{\mathcal{L}(\beta_s^{J/\psi\phi}, \Delta\Gamma, \vec{\xi})}{\mathcal{L}(\vec{\xi})}$$

Measurement of β_s

- Ideal case: produce fit value of β_s as we do for lifetime, etc.
- At current statistical level, fit shows some bias for β_s
- Instead, produce 2D likelihood contours in β_s - $\Delta\Gamma$ space
  - Perform fits on data with β_s and $\Delta\Gamma$ fixed at 400 points on 20x20 grid
  - Ratio of log likelihood value for fit at each point to the global minimum used to construct likelihood contour plots
- Use profile-likelihood ratio ordering technique to ensure coverage



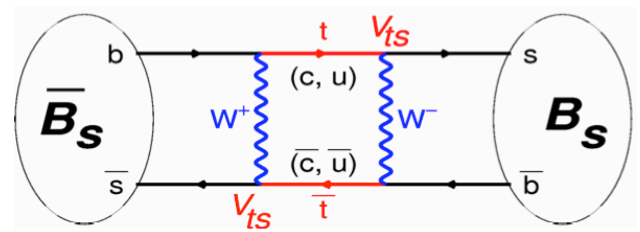
CP violation in neutral B_s system

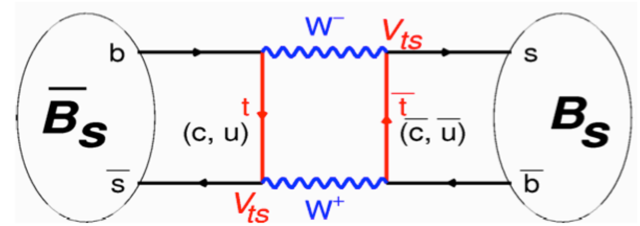
Flavour eigenstates:

$$|B_s^0\rangle = (\bar{b}s)$$
$$|\bar{B}_s^0\rangle = (b\bar{s})$$

Mixing of flavour eigenstates is governed by:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = H \begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} \equiv \Bigg[\underbrace{\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2} \underbrace{\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}}_{\text{decay matrix}} \Bigg] \begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$





Flavour eigenstates are not mass eigenstates:

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle$$
$$|B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle$$

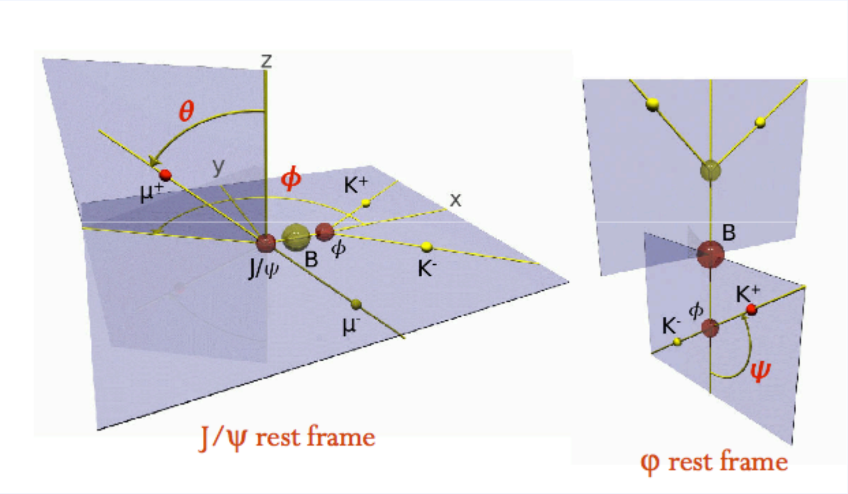
Different masses -> mixing frequency: $\Delta m_s = m_H - m_L \approx 2|M_{12}|$

-> phase: $\varphi_s^{SM} = \arg(-M_{12}/\Gamma_{12}) \sim 0.004$

Different decay widths: $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(2\varphi_s^{SM})$

Fit function: angular separation

Final state is a mixture of CP even (~75%) and odd (~25%) states.



$|A_0|^2$: polarisation longitudinal, parallel
$|A_{//}|^2$: polarisation transverse, parallel
$|A_{perp}|^2$: polarisation transverse, perpendicular

Three angular momentum states of J/ψ phi:

L=0	S-wave	**CP even**
L=1	P-wave	**CP odd**
L=2	D-wave	**CP even**

Can separate final CP states using angular variables

Transversity basis describes these contributions as: A_0, $A_{//}$ (CP even), A_{perp} (CP odd) according to their polarisation.

Can be separated using the angular distributions of the final state particles

Comparison of data periods